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Ceramic Tiles as Sustainable, Functional and Insulating Materials to Mitigate Fire Damage

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Abstract
Owing to their lower costs and functional properties, the construction industry has been increasingly adopting synthetic organic polymer (SOP) materials into linings, interiors and non-load bearing structural components. While SOPs have favorable properties and characteristics at ambient conditions, the same materials often perform poorly under moderate-to-elevated temperatures such as that arising from a building fire. In fact, most SOPs tend to combust and decompose at elevated temperatures which, unlike traditional building materials such as concrete and ceramic tiles, is proven to not only contribute to the fire but also to adversely affect evacuation and firefighting operations. From a fire engineering perspective, this paper tests a hypothesis in which ceramic tiles (CTs) are expected to outperform SOPs and commonly used insulations as finishing and lining materials under fire conditions. As such, this study showcases a thorough comparison between the behavior of commonly available CTs, SOPs and insulations in temperatures ranging between 25 to 1000°C. Then, this paper analyzes published CT models to derive temperature-dependent material models with the aid of machine learning (ML). Findings of this work advocate the use of CTs as favorable finishing and interior lining materials to enable realizing improved structural fire performance and fire response managements, as opposed to SOPs, composites or insulations. The outcome of this work is expected to be of interest to architects, first responders, building officials, fire and structural engineers.

Keywords: Material models; Ceramic tiles (CTs), Synthetic organic polymer (SOP); Artificial neural network (ANN); Genetic algorithm (GA).

1.0 Introduction
Commonly used building materials encompass a significant part of today’s construction industry. Such materials primarily include derivatives of concretes and steels, with improved properties (i.e. strength, chemical resistance, and increased resiliency to weathering etc.). Oftentimes, such materials are also supplemented with additives/fillers that are customizable to obtain unique microstructures, higher strength-to-weight ratios via specific fabrication/milling/production processes etc. These materials are mainly tailored and optimized for load bearing applications as to enable leaner and lighter structures and hence are predominantly used in the skeleton of a structural system [1,2]. Fortunately, the aforenoted materials do not combust and have been shown to have an adequate performance and stability under elevated temperatures (within 25-500°C) [3–5]. This delays failure under fire conditions and in turn allows safe occupants evacuation and firefighting operations.

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On the other hand, the interior of a structure (i.e. building compartments) often utilizes other types of building materials wherein their objectives are to provide aesthetics, comfort, storage, functionality to residents etc. Due to modernization and varying consumer preferences, such materials often leverage cheap and affordable composites (plastics) [6]. In general, plastics are synthetic organic polymers with higher molecular weights. These plastics are traditionally made from monomers including ethylene, propylene, styrene, amides, and urethane. Monomers, with or without further chemical modifications, can be used to fabricate different plastics such as high-density and low-density polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyamides (nylon), and polyurethane (PUR) polymers. Approximately 18-24% of annual global plastics produced are used in constructions [7,8]. Due to the nature of plastics, such materials tend to degrade with moderate rise in temperature (exceeding 100°C). This degradation not only adversely affect properties of plastics, but can also release smoke, and toxic fumes; further complicating evacuation and relief efforts. A key item to remember is that plastics are considered as fuels and could indeed facilitate fire growth and spread. This has been duly noted in recent fire incidents across the globe where different forms of plastics were directly linked to fire breakout and spread [9,10].

In 2017, the newly renovated 24-storey Grenfell tower (London, UK) faced a serious fire incident. This tower housed more than 600 people in 129 apartments. As part of its renovation, the tower received new windows and a two-component aluminum composite rainscreen cladding. The first component was Arconic's Reynobond PE (consisting of two, coil-coated, aluminium sheets that are bonded via fusion process to both sides of polyethylene-based core; and Reynolux aluminium sheets). This cladding component was followed by Celotex RS5000 PIR thermal insulation. On 14 June 2017, a fire started on the fourth floor of this building, and then quickly spread to upper floors on one side of the tower. This fire has caused 72 deaths and over 70 injuries and significant property damage. Ongoing investigations linked the poor performance of the composite cladding to the rapid spread of fire which caused the high toll of losses [11,12].

Another related fire incident occurred under the I-85 bridge, located in Gorgia, USA. This prestressed concrete bridge served 243,000 vehicles a day. In a recent official routine inspection, the bridge, achieved a rating of 94.6 out of 100, implying that the bridge to be in excellent service condition. On March 30, 2017 a fire broke out under the bridge due to burning of stored large Polyvinyl chloride (PVC) pipes. Due to this burning, temperatures rapidly grew to 900-1100°C. Within thirty minutes into fire arising from burning of PVCs, one span of 30.3 m long collapsed, while neighboring elements underwent significant damage. Post-fire probe uncovered major spalling in the concrete bridge. Damages in the aftermath to this fire-induced collapse were assessed to be close to $10 million [13]. Georgia Department of Transportation (GDoT) reported that it took weeks to repair the fire damaged bridge. During this repair process, a spike in significant traffic delays and detours, together with indirect economical losses, were reported.

It is for the above incident that civil constructions codes has historically favored utilizing inert construction materials to be able to withstand incidental events such as fire (as well as thermal loading effects) [14]. Since the majority of ambient temperature-induced effects are reversible;

much of material properties undergo minor, if any, changes. However, excessive temperature rise can permanently changes properties of a given material (i.e. density, thermal conductivity, and specific heat) due to the often irreversible complex pyrolytic and combustion processes of materials that are sensitive to temperature (i.e. plastics) [15]. The ability to withstand such effects is governed by the type of material and how properties of the material in question tend to change with rise in temperature. Oftentimes, representative samples from candidate materials are examined through standardized small-scale experimental fire tests as to measure its response once exposed to elevated temperatures as well as monitor its behavior in terms of fire spread and smoke generation. For example, ASTM E84 assesses surface fire spread, ASTM E648 determines fire resistance under heat load, and ASTM E662 test whether material generates smoke [16–20]. Although these tests provide useful information about material fire properties such as surface burning, ignitability, and smoke generation, these tests do not assess physical or chemical changes within the tested specimens during or post exposure to elevated temperatures.

Due to the concrete-like properties of CTs, this paper carries an investigation to properly examine the notion that CTs, can be comparable to commonly used insulation, and may in fact outperform SOPs as finishing and lining materials in structures with high vulnerability to fire. This paper starts with a review comparing temperature-dependent thermal properties of CTs and SOPs. Then, this paper analyzes such properties using ANNs and GAs to develop temperature-dependent models for these materials. The outcome of this study showcases how CTs can be favorable finishing and interior lining as well as insulation materials in structures with high vulnerability to fires.

2.0 Overview of Temperature-dependent Tests

Proper analysis on materials used in construction requires a thorough evaluation of both thermal and mechanical properties both at ambient and fire conditions. Although such testing at ambient conditions is possible and with ease, testing materials at high temperatures could be challenging. This is due to the lack of: expertise, standardized testing methods, testing equipment, and complexities ensuring fidelity and reliability of sensor detection at elevated temperatures etc. [21–23]. As a result, only a few studies on high-temperature performance are available compared to that of ambient conditions. From the perspective of this study, and for brevity, only the thermal properties of CTs and SOPs from a fire engineering and thermal insulating properties will be highlighted.

From fire protection point of view, thermal properties such as density, specific heat capacity, and thermal conductivity are of utmost significance. All these depend on the molecular-level chemical sensitivities and physical integrities to heat. Although ambient temperature (or heat loads) have effects on chemical bonds, the majority of those changes are minor. Rarely, even those physical property changes are observable to a naked eye. However, at higher temperatures (>100°C), organic molecules such as SOPs and filler organic compounds volatilize, break into smaller molecules through pyrolytic and oxidation reactions. For example, commonly used plasticizers in polyvinyl chloride (PVC) products are liquids at room temperatures; therefore, they could be highly volatile or flammable (with or without heat). Not only volatile organic compounds (VOC) release but also molecular degradation reactions could be accelerated with increasing temperatures

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and heat loads. At elevated temperatures, the initial thermal degradation could occur at the least thermally stable bond due to the rise in thermal energy (heat) [24]. Heat causes chemical degradation via pyrolysis, a chemical change by heat in the absence of oxygen, or via thermal oxidation by both heat and oxygen. When the temperature reaches a critical point, the majority of bonds fail, resulting in disintegration, heat generation, and combustion (flaming). Briefly, those same SOPs that were part of construction materials are a source of fuels to initiate and sustain fires. Generally, organic compounds comprise carbon, and they have heat-sensitive chemical bonds with other atoms such as hydrogen, nitrogen, and oxygen, and they are highly flammable than their counter parts inorganic compounds of similar mass.
This brings in the notion of heat release rate (HRR); which provides a quantitative mean to measure how materials can generate heat in a fire scenario – with the notion that materials generating low HRR do not worsen fire. Two questions arise herein: (1) would heat released from construction materials worsen fire growth or help accelerate fire growth and spread?, and (2) whether such materials will facilitate a much longer-burning (intense) fire, as opposed to other inert materials? [25]. While scrupulous SOP construction materials may have fire retardant additives, these additives may be of partial help and can only limit combustion of SOPs, up to a certain temperature range (100-200°C). beyond such conditions, SOPs are more likely to decompose and melt; thus, releasing toxic fumes and gases which can obstruct evacuation and egress operations.

Flame spread is another test method that can be tested by ASTM E84 (or NFPA 255 or UL 723). This method assesses fire spread over a combustible surface. That is how rapidly fire spreads, and whether such a spread will over a sizable area that may warrants concerns. Ventilation (wind aided and opposed) factors determine the severity of fire hazard; and hence, flame spread. However, these test methods may not be quite suitable for testing SOPs such as thermosetting plastics because plastic melt and stops fire spreads [26]. In general, there are three classes (Class A, Class B and Class C). Class A materials are often associated with the lowest flame spread. To meet this class, a material must meet the required flame index of 25 and smoke index of 450.

Combustibility (and non-combustibility) is another thermal-related property that determines the magnitude of fire growth and spread of potential fire fuels. The non-combustibility test method adopted by the ASTM E136 test applies a temperature of 750°C to test specimens [27]. This testing method has three criteria to pass or fail the tested materials. These include that: (1) neither the temperature on the surface nor in the center of the tested specimen rise by more than 30°C above the furnace temperature (to confirm that noncombustible materials do not emit heat or non-exothermic reactions at 750°C), (2) flames do not develop from the tested specimen after the first 30 seconds of exposure, and (3) that no more than 50% of the specimen mas loss during testing (to ensure that tested material is not losing weight by releasing gases or sublimation). Unlike ceramic tiles, SOPs often fails in non-combustibility primarily due to their tendency to ignite or mass loss.

3.0 Observations from High Temperature Material Tests

Thermal energy and material interaction result in atomic and molecular scale changes. Some of those atomic and molecular level changes are not reversible or permanent because materials may lose its volatile compounds with heat, oxidized to form gases, or release flumes from burning materials. Therefore, a significant portion of heat-caused matter changes leading to observable physical property changes in density, heat capacity, and thermal conductivity. This section reviews these three properties for ceramic tiles, SOPs and common insulations and these often govern thermal response and fire resistance analysis.

Figure 1 shows the density changes in CTs with temperature from ambient to 1000°C based on a collection of studies [28–41]. This figure clearly shows two unique trends: (1) the density of CTs is fairly stable up to 1000°C, and (2) density of CTs could potentially slightly increase with rise in temperature. The stable nature of CTs is often attributed to the lack of atomic or molecular changes such as loosing volatile compounds and oxidation products [42]. Another reason would be due to the firing-based fabrication of CTs which occurs at high temperatures. During this firing process, a number of processes take place. For example, raw materials loose water at around ~100°C, organic matters decompose (~200°C), dihydroxylate (~400°C), silica inverts (~500 °C), carbonates decompose (~800 °C), finally sintering and glass transition (~1000 °C) [42]. Thus, once CTs cools down, these materials turn inert wherein all reactions or any other heat-absorbing and emitting reactions, have been completed (i.e. that is, their chemical composition unlikely to change, thereby maintain stable densities with heat up to 1000°C). One should note that some researchers reported a slight increase in density beyond 1000°C and this could be related to silica inversions and glass transitions. On other hand, a few works reported that the density of fiber reinforced polymers (FRPs) often used in structural applications remains somehow at a steady level up to about 500-550°C. At temperature exceeding this range, the density then undergoes a decrease of about 20% after which it stabilizes [43]. A series of tests conducted by Kodur and Shakya [44] on spray applied fire resistive materials (SFRMs) have shown that commonly available insulation materials have low density which reduces at high temperatures. These researchers tested three SFRMs at ambient conditions was measured to be 0.298 g/cm^3 for CAFCO, 0.423.3 g/cm^3 for Carboline and 0.451.8 g/cm^3 for WR-AFP. The same property dropped to 0.235, 0.236, and 0.366 g/cm^3, respectively.

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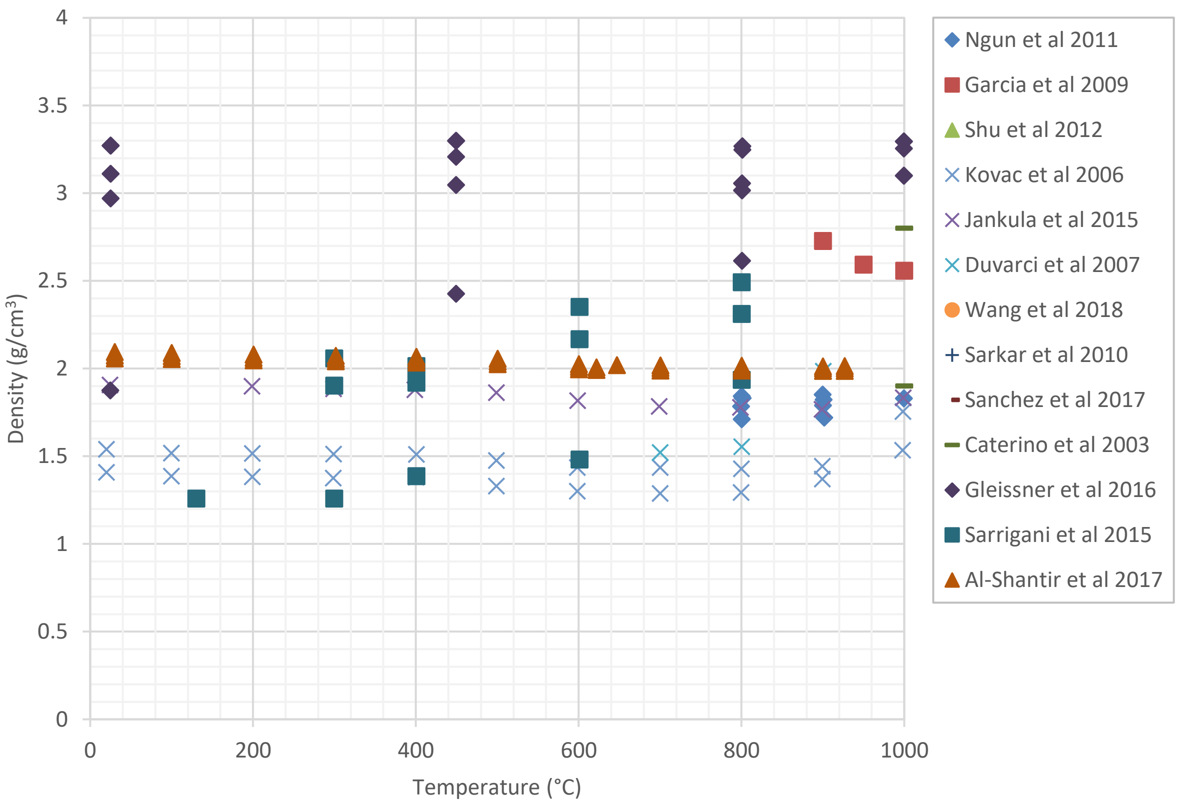

Fig. 1 Variation of densities in CTs as a function of temperature

The thermal conductivity measures the ability of a material to transfer a unit of heat. Dehydration, dehyroxylation and decarbonation reactions reduce thermal conductivity of CTs [45]. Besides fired CTs have unevenly distributed high porosity that reduce thermal conductivities [45,46]. Uneven and small porous structures are a hindrance for conductive heat transfer; and hence shows the low thermal conductivity of CTs as reported by [29,45,47–55] (see Fig. 2). The thermal conductivity of SOPs (or FRPs) were rarely reported in the literature. Of the few works available; this property was measured at temperature range between 25-300°C (as these materials lose their integrity beyond this range) and was shown to slightly vary from 0.6-0.8 W/m.K. On a parallel work, Kodur and Shakya [44] noted that the much lower thermal conductivity of SFRMs at room temperature (within 0.07–0.2 W/m.K). However, these researchers noted how the thermal conductivity can increase at temperature beyond 300°C as SFRMs dry and shrink due to water evaporation. Kodur and Shakya [44] also reported that out of all three insulation materials, CAFCO-300 has the lowest thermal conductivity. CAFCO-300 was then followed by Carboline Type-5MD and Tyfo WR-AFP. The same researchers also reported that Carboline Type-5MD exhibits the least sensitivity in thermal conductivity with temperature.

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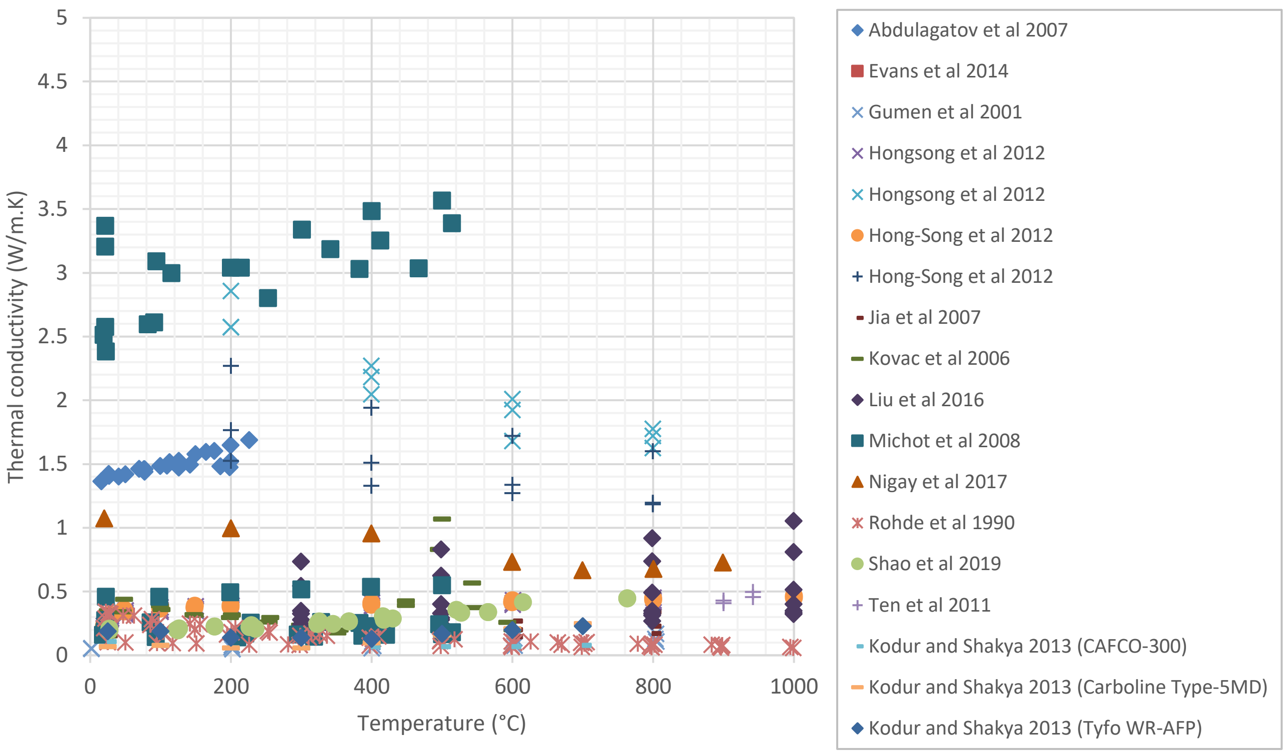

Fig. 2 Variation of thermal conductivity in CTs and insulation materials as a function of temperature

The specific heat describes the amount of heat required to raise a unit mass of material a unit temperature. Based on a number of works, Fig 3 shows that CTs have relatively constant heat capacities from ambient to 1000°C [35,47,49,51,53,54,56–60]. Generally, water, organic compounds, and hydroxyl group absorb heat for molecular vibrations; the molecule motions results in kinetic energy transfer to neighboring particles. Lack of these compounds as free molecules to interact with heat could keep CT heat capacity low and nonfluctuating with temperature. The specific heat of FRPs is reported to significantly varies with any rise in temperature. In one study, Kalagiannakis and Van Hemdrijck [61] estimated that the ambient temperature specific heat for both glass and carbon/epoxy FRPs to be 800 J/kg-K. In a parallel recent work carried out on insulation materials, Kodur and Shakya [44] reported that the specific heat of the three tested SFRMs in their study was in the range of 700–3000 J/kg.°C and that this property only marginally changes with rise in temperature. They also reported that this property is governed by the density of a given SFRM – wherein SFRMs with low density tend to have high specific heat.

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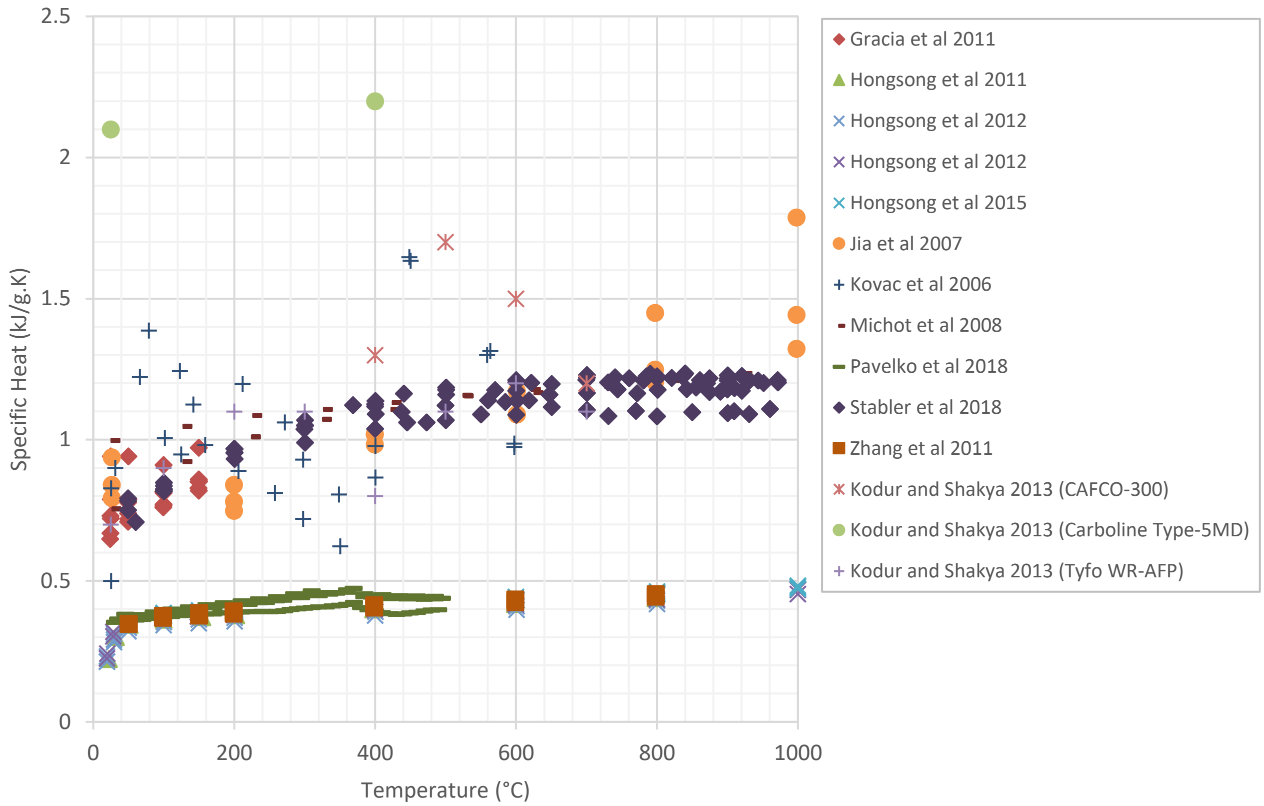
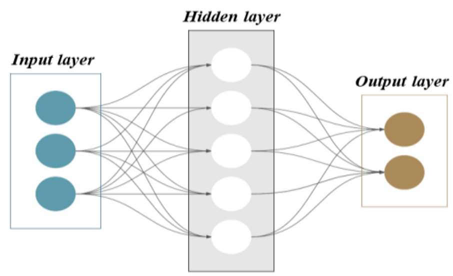


Fig. 3 Variation of specific heat in CTs and insulation materials as a function of temperature

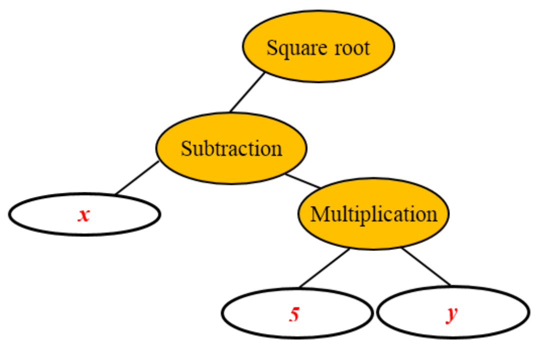
4.0 Development of an Artificial Intelligent Model

While traditional analysis methods may require a set of assumptions or presence of knowledge on relations between governing factors, artificial intelligence (AI), on the other hand does not require such assumptions to start an analysis nor a lengthy evaluation procedure [62]. All in, AI attempts to mimic the reasoning process carried out by the brain. The rationale behind using ANN, in a form of AI, as the main technique to arrive at a holistic understanding of CTs' behavior under high temperatures arises from the unique capability of ANNs to identify patterns hidden within observations (which in this case are obtained from material tests carried out at elevated temperatures) through methodical reasoning.

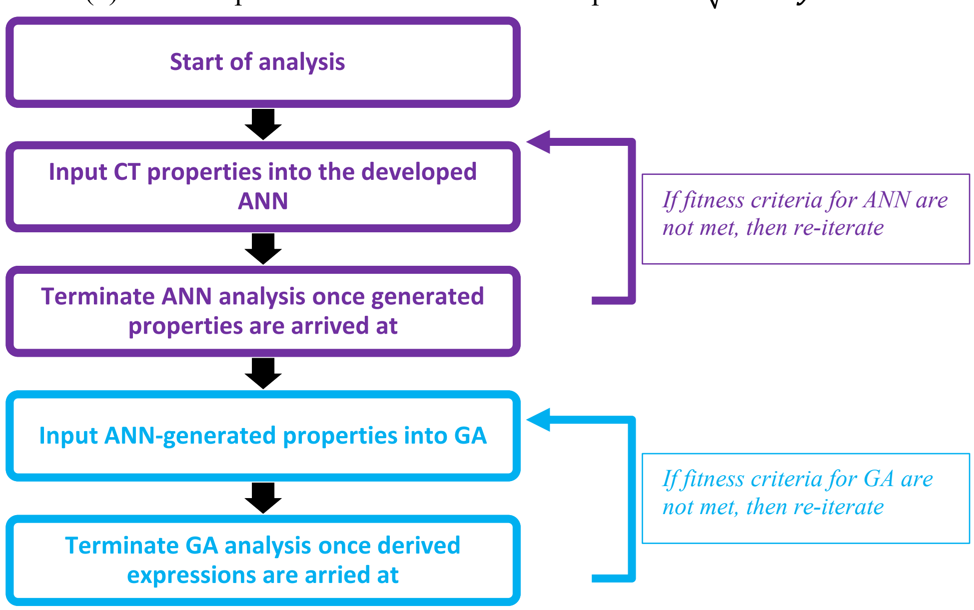
From this view, an ANN comprises of a set of layers that are to be arranged in an optimized topology. Each of these layers contains a number of neurons. These neurons vary in each layer depending on the complexity of the problem in hand (i.e. examining thermal material properties in CTs and SOPs). A typical illustration of an ANN is shown in Fig. 4. This figure shows three different layers. The first layer, as called the input layer, contains the temperature-dependent material properties. The first layer is also connected to middle or hidden layer(s). The hidden layer(s) has the ability to establish linear and/or non-linear relations through transformative operations. On the other side, the hidden layer(s) is also connected to the output layer. In this work, a multilayer perception ANN that has "feed-forward back-propagation and supervised learning", as inspired by topology of the human brain, is used to develop the ANN [63].



(a) Layout of an ANN



(b) A tree representation of a GA-based expression: $\sqrt{\boldsymbol{x-5y}}$



(c) Analysis procedure

Fig. 4 Methodology followed in this study

Once the above topology of the ANN is defined, the newly developed ANN is then used in the training stage. In this stage, the ANN is primed to understand how do CTs property patterns change under elevated temperatures. The goal is to realize a holistic interpretation that exemplifies the thermal properties of common CTs. An ANN can be built through the deep learning tool in MATLAB [64] or via other commercial software. Before the ANN analysis starts, the compiled data, as obtained from the literature review and that plotted in Sec. 3, is first randomly arranged to minimize and limit biasness of a specific study, CT type, or testing procedure [65]. Then, this data is split into two sets. The first set (made of 70% of all data points) was used to train the ANN and the set of data were used to test the performance of ANN. This split percentage was arrived at from suggestions of similar works [66,67][1].

The training stage of this ANN starts by analyzing temperature-dependent thermal properties (say, values of specific heat at target temperatures; 100, 200, 300… and 800°C, as reported by various researchers, and so on for other properties). This analysis applies random weightages in a series of transformative operations and transfer function (i.e. tangent etc.) [68]. Transformed outputs from this analysis are then totaled to generate predictions (i.e. ANN-predicted values for specific heat, thermal conductivity and density at particular temperatures, i.e. 25, 100, 200 ... 800°C). those values are then treated by a genetic algorithm (GA) based model [69] (see Fig. 4). In GA, a search process that mimics the Darwinian concept of survival of natural selection is applied to derive predictive expressions that best fit the ANN-predicted values.

In this step of analysis, the GA model initiates the search by starting with a random set of candidate expressions. Such expressions reflect solutions stitched together through randomly generated arithmetic and mathematical operators i.e. multiplication (×), logic (i.e. OR) etc. These expressions can be finetuned via naturally-inspired operations, i.e. mutation (alternation) and/or crossover (combining two, or more solutions) until an optimal expression is obtained. The optimal expression is one that satisfies predefined fitness metrics; such as correlation coefficient (R) and/or maximum error (ME), with a focus to favor compact and easy-to-apply expression. Additional details on this AI model can be found in previous works which applied a similar approach to construction materials [2,70].

5.0 Derivation of AI-based Thermal Material Models

In this work, the thermal material properties investigated herein are density, thermal conductivity, and specific heat. The effectively developed ANN was used to estimate generalized thermal-based temperature-dependent material models for commonly used CTs, and then the GA model was used to derive simple expressions to represent such models.

[1] The authors would like to point out that other researchers have also used a different split ratio (i.e. 80/20)[80,81]. It is worth noting that the split ratio is often sensitive to the number of data points used and its effect can be obvious in small datasets. During this work, a 70/30 split was optimal (and yield quite similar results to an 80/20 split due to the large number of data collected) and hence we applied a 70/30 split. Future works are also encouraged to explore k-fold cross validation methods [82].

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Overall, one can see that predictions from the developed ANN fall within that of reported data points in all cases for density, thermal conductivity, and specific heat (see Fig. 5). In addition, the developed AI model also managed to reach a good correlation performance as can be observed by evaluating two indicators (correlation coefficient (R) and mean absolute error (MAE)) (see Eqs. 1 and 2) [71]. It is due to this good agreement that it can be inferred that the developed AI model was able to capture the temperature-dependent behavior of common CTs.

Correlation coefficient (R):

$$R = \frac{\sum_{i=1}^{n}(A_i-\overline{A}_i)(P_i-\overline{P}_i)}{\sum_{i=1}^{n}(A_i-\overline{A}_i)^2\sum_{i=1}^{n}(P_i-\overline{P}_i)^2} \qquad \text{Eq. 1}$$

where P_i and A_i are predicted and actual values, respectively.

Mean average error (MAE):

$$MAE = \frac{\sum_{i=1}^{n}|E_i|}{n} \qquad \text{Eq. 2}$$

where *E* is the error between predicted and actual values for a particular temperature, *n* is the total number of observations.

In lieu of the above performance metrics and validation plots, few researchers proposed other means to evaluate a given numerical model. For example, Smith [72] suggested that correlation coefficient (R) that exceeds 0.8 implies a strong correlation. Figure 5 and Table 1 show that all ANN-predicted properties and GA-derived expressions have a R far exceeding 0.8, and thus satisfying this criterion. Frank and Todeschini [73] proposed another criterion in which a minimum ratio of 3 is to be maintained between the number of observations and input parameters. In this work, these ratios were 90, 145, and 177 for density, thermal conductivity, and specific heat, respectively. It is clear that both of these additional criteria are also satisfied.

In general, the presented analysis showcases that CTs have superior thermal properties to that of SOPs, and comparable to that in concrete (from fire resistance point of view) and hence are favorable for use in constructions as finishing or lining materials. Ceramic tiles also share main characteristics of SFRMs and since CTs do not decompose, or undergo significant degradation under fire conditions, unlike SFRMs. The use of CTs could be much more feasible and economical as these materials may not require to be replaced post a fire incident. A dedicated discussion on this aspect is provided in the following section.

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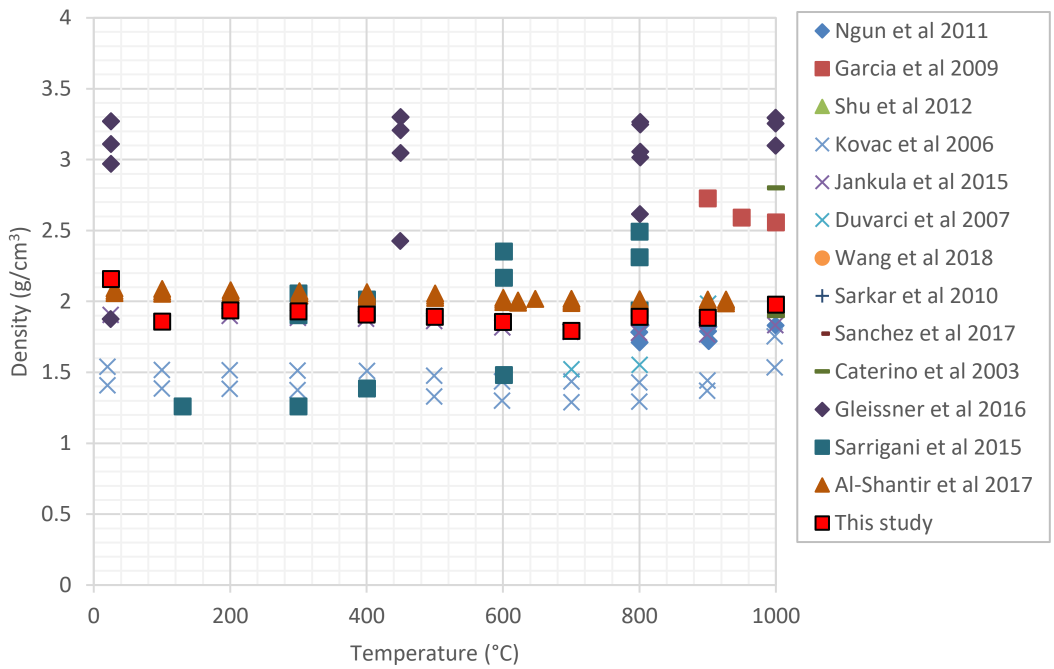
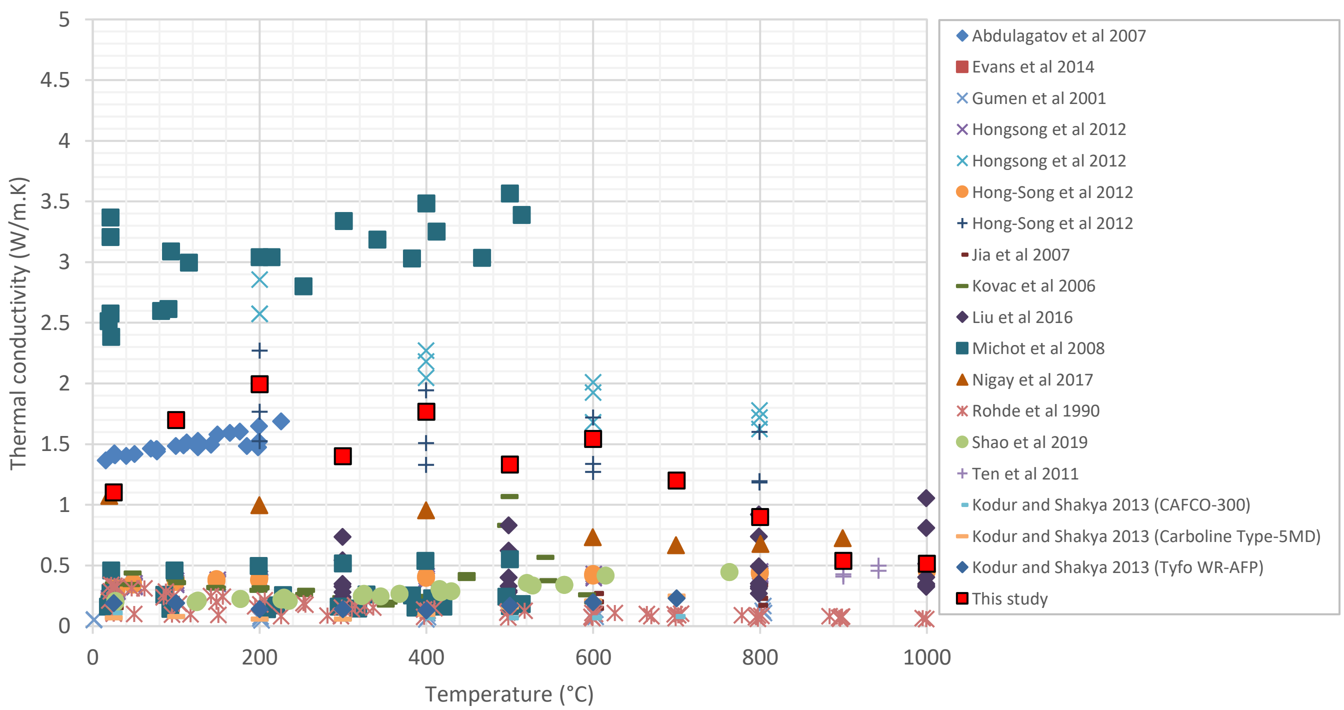


(a) Density



(b) Thermal conductivity

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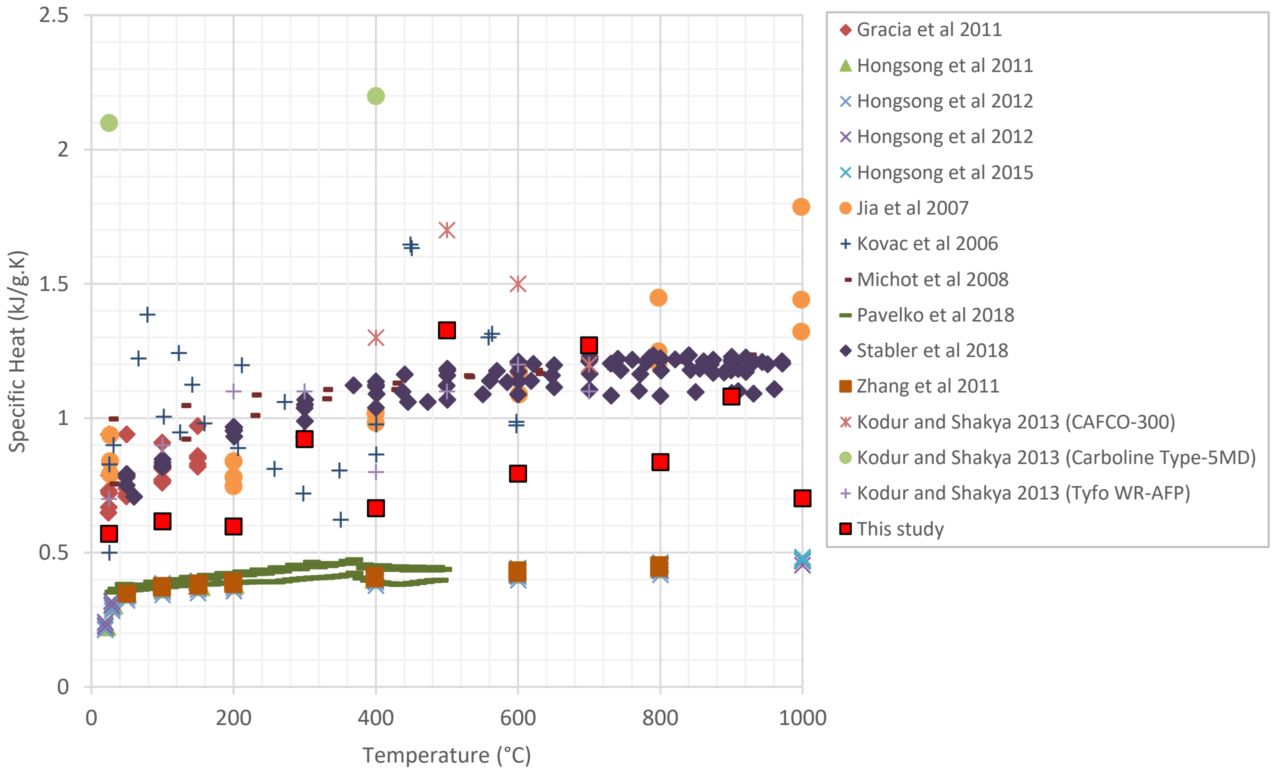

(b) Specific heat

Fig. 5 Comparison between predicted and measured thermal properties in CTs and insulation materials as a function of temperature

Table 1 GA-derived expressions and ANN predicted values for temperature-dependent material properties

Property	**Expressions and values**											***R* (%)**	***ME***
Density (kg/m^3)	$\rho = 1.72e^3 + 0.325T + \exp(30.9 - T) - 128\sin(5.83 + T)$											97.2	13.3
	Temperature range and values												
	25	100	200	300	400	500	600	700	800	900	1000		
	2158	1858	1938	1931	1909	1893	1858	1793	1892	1887	1980		
Thermal conductivity (W/m.K)	$k = 1.86\log(\log(T)) - 1.07 - 0.000303T\log(T - 5.34 - T\cos(0.535T))$											97.1	0.07
	Temperature range and values												
	25	100	200	300	400	500	600	700	800	900	1000		
	1.10	1.70	2.00	1.40	1.77	1.33	1.54	1.20	0.90	0.54	0.52		
Specific heat (J/kg.k)	$c = 773 + 0.0798T - 2.09e^{-14}T^5$											99.8	0.59
	Temperature range and values												
	25	100	200	300	400	500	600	700	800	900	1000		
	571	616	598	923	666	1328	795	1272	837	1081	702		

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6.0 A View on CTs as Thermal Insulators

Given that the above analysis has enabled us to arrive at generalized thermal material models for CTs, these models can now be compared against those of commonly available insulation materials such as SFRMs, glass and rock fiber insulations and Gypsum wall boards (Type X). This comparison is plotted in Fig. 6. This figure also shows generalized thermal material models for thermal conductivity and specific heat of normal strength/weight carbonate and silicate concretes as obtained from an earlier work [2]. This figure depicts few interesting observations. For a start, one can see that the thermal conductivity of CTs is very similar to that of concretes. This is expected given the similar composition and minerals used in both of these materials. While SFRMs, glass and rock fiber insulations and Gypsum Type X are specifically designed insulation materials, these insulations have much lower thermal conductivity than that of concretes and CTs. However, this conductivity seems to increase with rise in temperatures – a feature not observed in CTs nor concretes. The rise in thermal conductivity in the case of SFRMs and Gypsum Type X is due to drying and shrinkage. One should note that this property was only reported for SFRMs up to 700°C. Their behavior beyond this point remains to be investigated.

The specific heat of CTs is generally lower than the other materials plotted in Fig. 6b. Still, this property remains within a close range of such materials at temperatures exceeding 500°C. On a parallel note, the density of CTs and concretes are very comparable. Just like CTs, normal strength/weight concrete has a typical density in the range of 2100–2300 kg/m^3. The temperature-induced loss in density causes it to slightly reduce by 100 kg/m^3 and which then stables beyond 100°C due to water loss. However, the same cannot be true for SFRMs, fiber insulations and Gypsum Type X which can be in excess of 10-20% of their original density as reported by Sultan [74], Benichou et al. [75] and Kodur and Shakya [44]. The above implies that properly designed CTs could potentially be used as thermal shields/insulators given that they are aesthetically pleasing, durable (does not deteriorate or spall under fire conditions – unlike SFRMs and concretes), easy to install, relatively cheap and sustainable [76].

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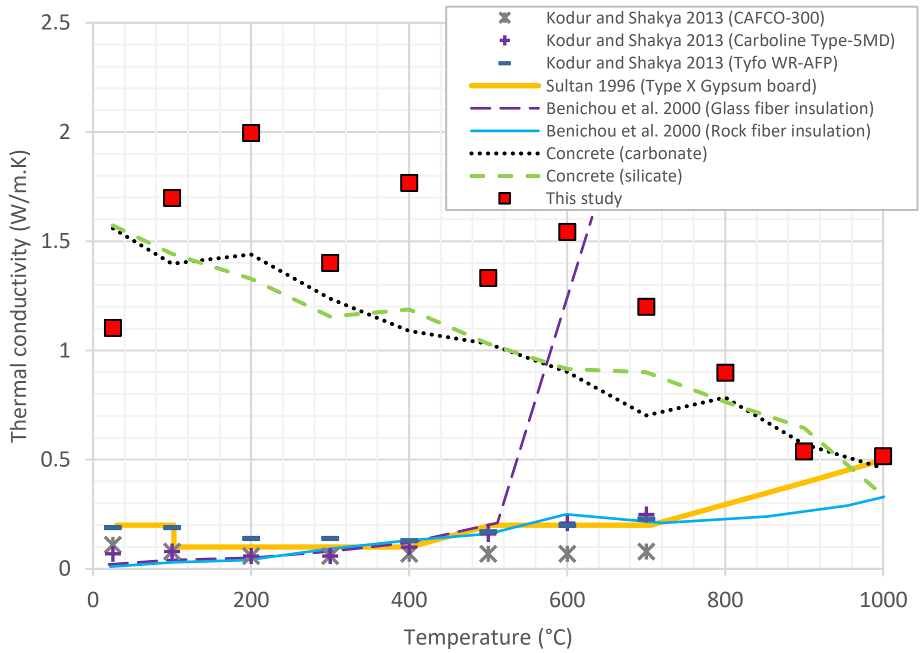
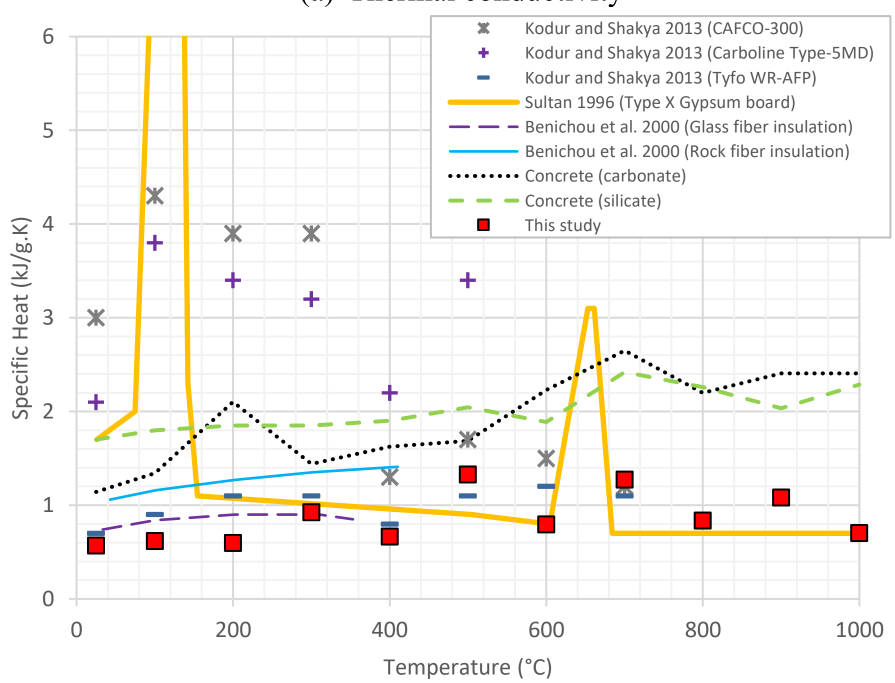


(a) Thermal conductivity



(b) Specific heat

Fig. 6 Comparison between generalized material models for CTs, concretes, SFRMs, glass and rock fiber insulations and Gypsum wall boards (Type X)

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7.0 Practical Implications and Future Directions

The thermal material models derived in this study are obtained using an ANN-GA coupled analysis that was carried out on a collection of properties and material models collected from various studies. The intent of this work is to showcase a holistic overview in property variations arising from material origin, testing methods/set-ups/heating rate etc. As such, it is expected that these thermal models can be used to express the overall thermal behavior of CTs. One should still note that the derived thermal models can further be enhanced through a number of means, for instance: (1) integrating additional material models to cover a wider range of variation in lieu of those plotted in Figs. 1-3, (2) utilizing other/optimized AI algorithms such as Support Vector Machines (SVM), Swarm models etc., and (3) specifically accounting for additional parameters related to fabrication and curing, chemical composition etc. While a common notion is that ceramics are naturally brittle materials, future studies are encouraged to explore mechanical (bending strength, cracking strength etc.), physical (i.e. porosity, water absorption etc.), bonding and post-fire properties, as well as integrity, of such materials to further ensure their adequacy and fidelity in post-fire scenarios [77,78].

As discussed above, the use of AI to analyze material properties requires the development of large databases. An advantage of compiling such databases ensures both transparency and constant updating of temperature-dependent thermal material models (due to continually changing fabrication process, testing procedures etc.). Given that AI approaches have the capability to self-improve with little supervision and with increased data flow, then the use, as well as accessibility, of such databases becomes advantageous. A collaboration between researchers of different engineering and materials backgrounds can help to facilitate that [79].

8.0 Conclusions

This paper fosters the notion that ceramic tiles can be used as efficient, aesthetic and cost-effective materials to substitute synthetic organic polymer as interior and lining materials in civil construction (i.e. buildings, bridges and tunnels etc.). In this pursuit, this paper presents a comparison between premature-dependent thermal material models for ceramic tiles and synthetic organic polymer as well as derivation of such model. This derivation was carried out by applying a coupled sequence of Artificial Neural Networks (ANNs) and Genetic Algorithms (GAs). Other conclusions from the results of this investigation are also listed herein:

- Due to their inert nature and similarity to traditional concretes, ceramic tiles could be effective as both functional and thermal insulating materials. The use of ceramic tiles is encouraged in constructions with high vulnerability to fire conditions.
- Ceramic tiles, when selected properly, can behave as thermal shields as opposed to composite materials often used in linings and flooring which could combust under fire conditions.
- There seems to be a lack of general guidance on conducting and developing material tests for ceramic tiles at elevated temperatures.
- Integrating AI techniques to analyze and develop material models (such as ceramic tiles) is proving helpful in modernizing fire assessment of materials and structures.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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